US Army Corps
of Engineers®

HSR Modeling for River Engineering and Design

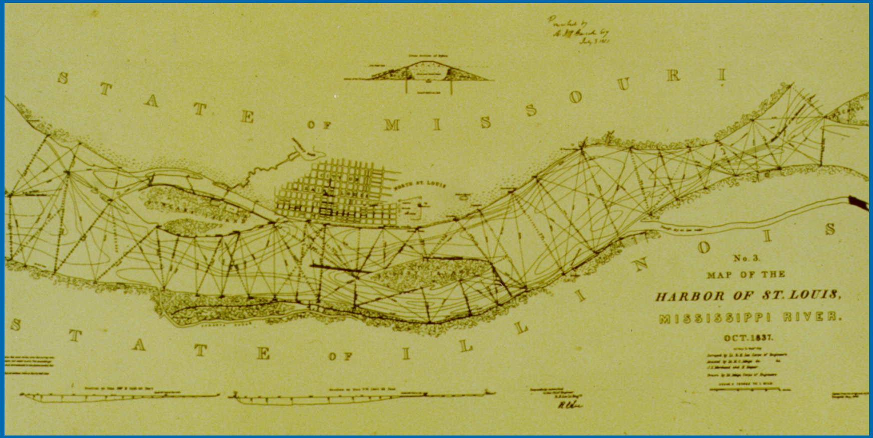
One Corps Serving the Armed Forces and the Nation

How Do Engineers Predict and Control Sediment Movement & Deposition?

Tools Used Include:

- Experience & Intuition
- Experimentation
- Mathematical Equations
- ***Physical River Modeling***

Experience & Intuition!


STATE OF MISSOURI
STATE OF ILLINOIS
No. 3.
MAP OF THE
HARBOR OF ST. LOUIS.
MISSISSIPPI RIVER.
OCT. 1837.

U.S.
MISSISSIPPI

Lt. Robert E. Lee was one of the 1st river engineers

Lt. Lee used his experience to design structures that saved the St. Louis Harbor

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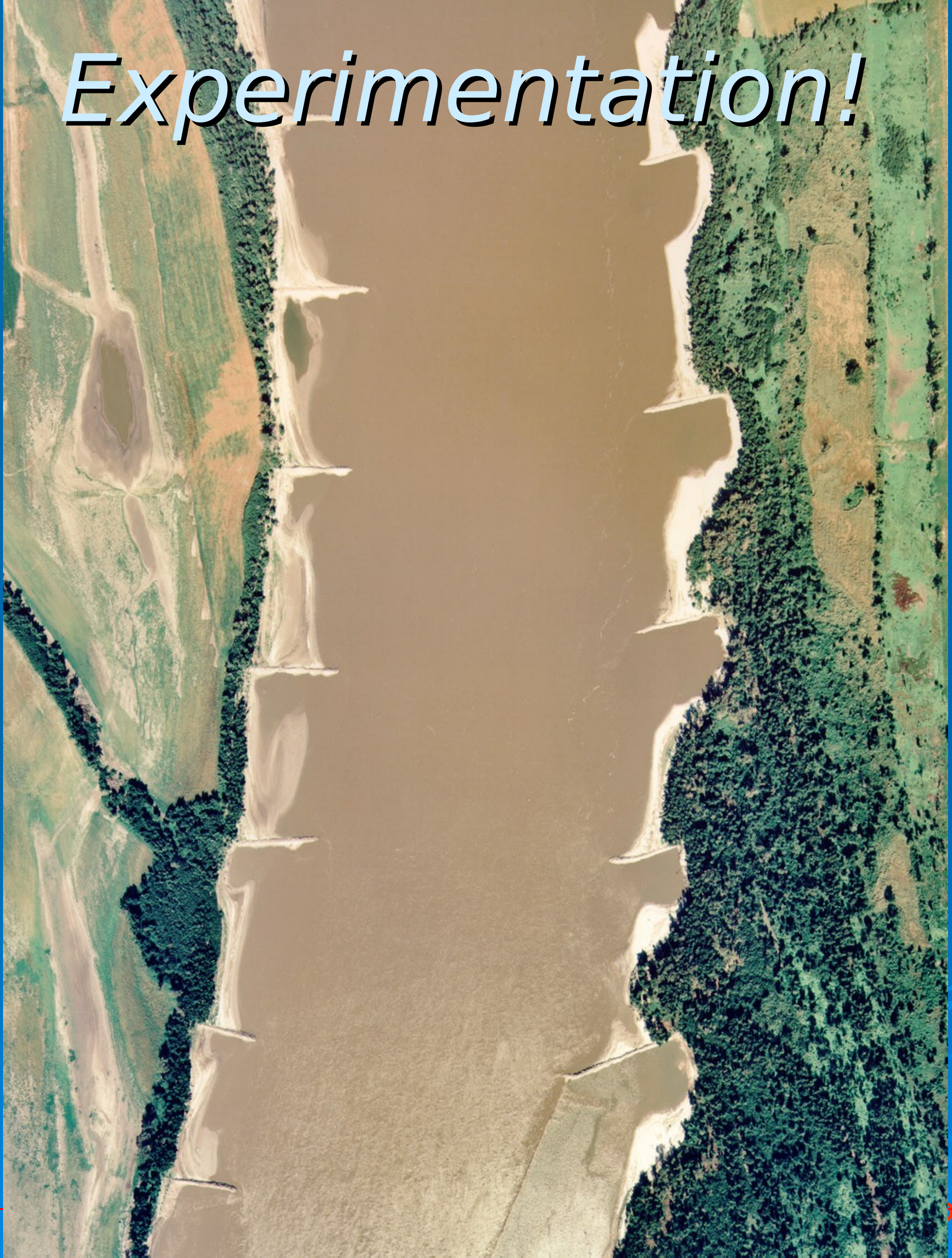
Experimentation!



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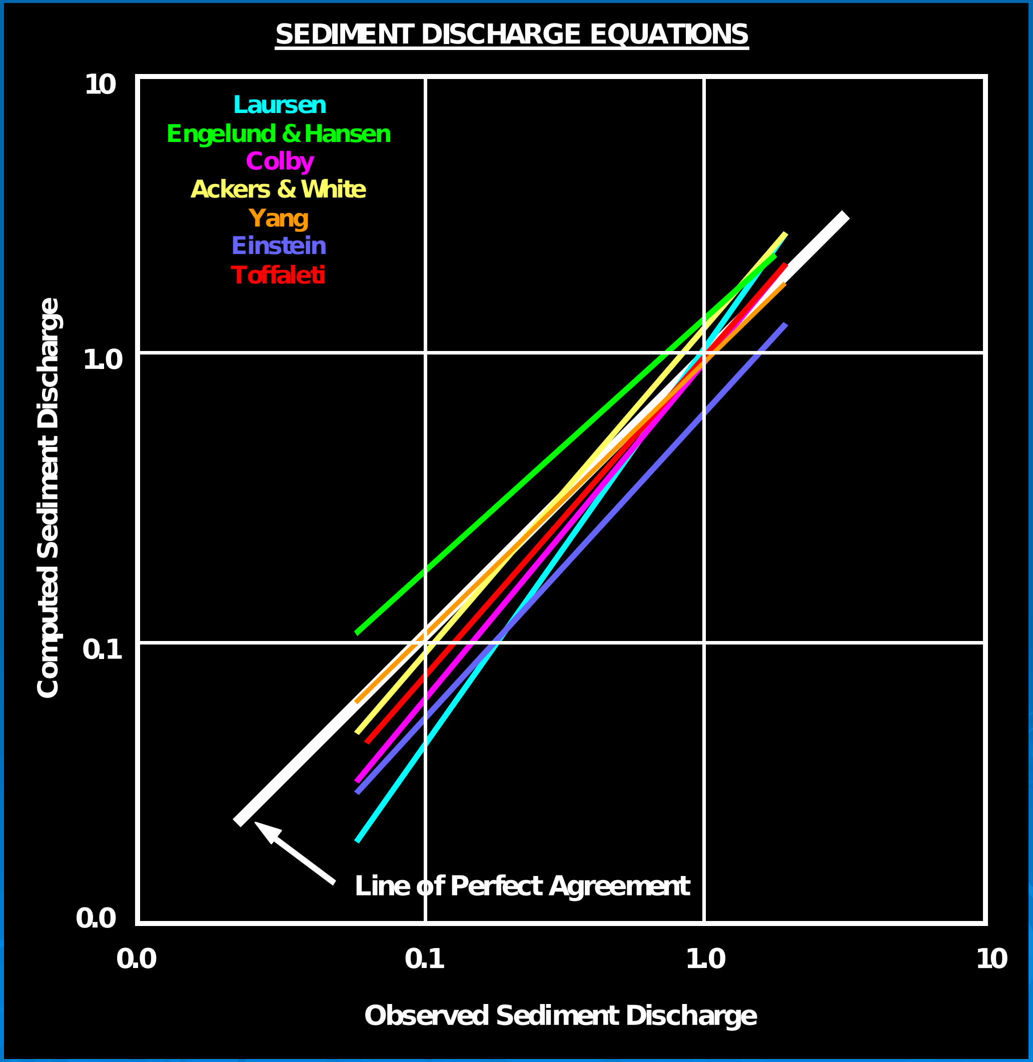
Mathematical Equations!

Albert Einstein

Einstein's Bed Load Equation

$$\varphi = \frac{q_B}{\gamma_s}\left[\frac{\rho}{\rho_s - \rho}\,\frac{1}{g d^3}\right]^{\frac{1}{2}}$$



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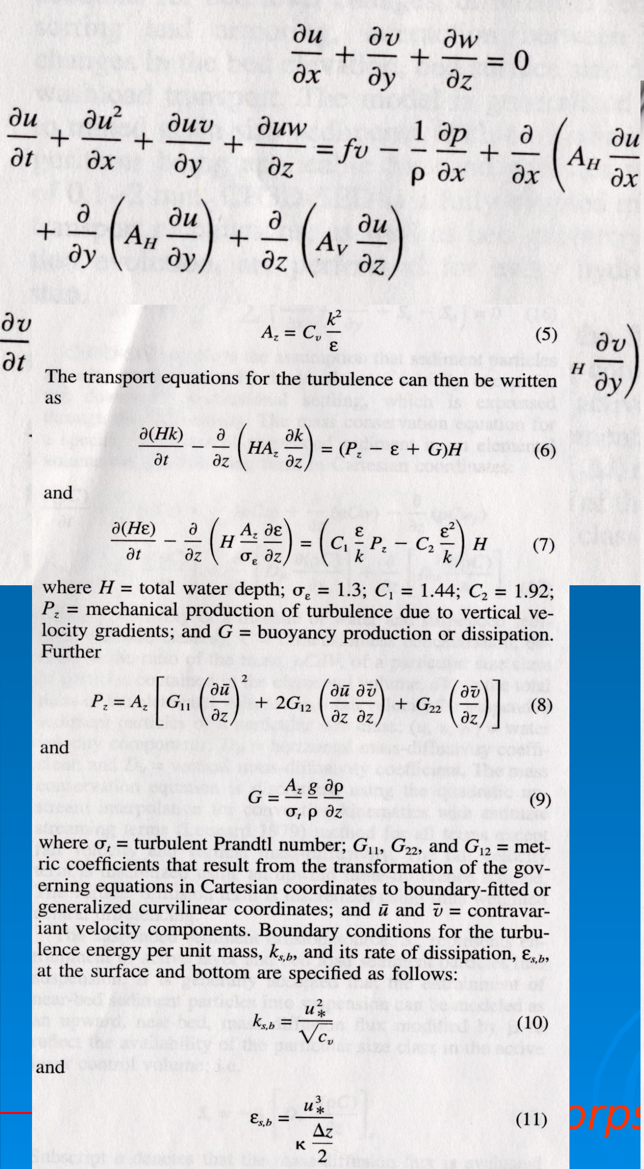
Typical Theoretical Sediment Transport Equations!



$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \qquad (1)$$

$$\frac{\partial u}{\partial t} + \frac{\partial u^2}{\partial x} + \frac{\partial uv}{\partial y} + \frac{\partial uw}{\partial z} = fv - \frac{1}{\rho}\frac{\partial p}{\partial x} + \frac{\partial}{\partial x}\left(A_H \frac{\partial u}{\partial x}\right) + \frac{\partial}{\partial y}\left(A_H \frac{\partial u}{\partial y}\right) + \frac{\partial}{\partial z}\left(A_V \frac{\partial u}{\partial z}\right)$$

$$A_z = C_v \frac{k^2}{\varepsilon} \qquad (5)$$

The transport equations for the turbulence can then be written as

$$\frac{\partial(Hk)}{\partial t} - \frac{\partial}{\partial z}\left(HA_z \frac{\partial k}{\partial z}\right) = (P_z - \varepsilon + G)H \qquad (6)$$

and

$$\frac{\partial(H\varepsilon)}{\partial t} - \frac{\partial}{\partial z}\left(H \frac{A_z}{\sigma_\varepsilon}\frac{\partial \varepsilon}{\partial z}\right) = \left(C_1 \frac{\varepsilon}{k} P_z - C_2 \frac{\varepsilon^2}{k}\right) H \qquad (7)$$

where H = total water depth; $\sigma_\varepsilon = 1.3$; $C_1 = 1.44$; $C_2 = 1.92$; P_z = mechanical production of turbulence due to vertical velocity gradients; and G = buoyancy production or dissipation. Further

$$P_z = A_z \left[G_{11}\left(\frac{\partial \bar{u}}{\partial z}\right)^2 + 2G_{12}\left(\frac{\partial \bar{u}}{\partial z}\frac{\partial \bar{v}}{\partial z}\right) + G_{22}\left(\frac{\partial \bar{v}}{\partial z}\right)\right] \qquad (8)$$

and

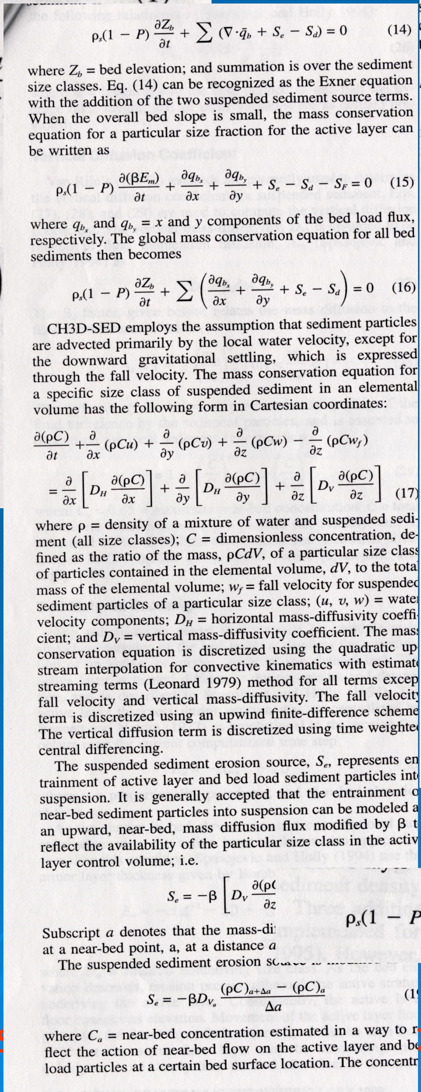
$$G = \frac{A_z}{\sigma_t}\frac{g}{\rho}\frac{\partial \rho}{\partial z} \qquad (9)$$

where σ_t = turbulent Prandtl number; G_{11}, G_{22}, and G_{12} = metric coefficients that result from the transformation of the governing equations in Cartesian coordinates to boundary-fitted or generalized curvilinear coordinates; and $\bar{u}$ and $\bar{v}$ = contravariant velocity components. Boundary conditions for the turbulence energy per unit mass, $k_{s,b}$, and its rate of dissipation, $\varepsilon_{s,b}$, at the surface and bottom are specified as follows:

$$k_{s,b} = \frac{u_*^2}{\sqrt{c_v}} \qquad (10)$$

and

$$\varepsilon_{s,b} = \frac{u_*^3}{\kappa \frac{\Delta z}{2}} \qquad (11)$$



$$\rho_s(1 - P)\frac{\partial Z_b}{\partial t} + \sum (\nabla \cdot \bar{q}_b + S_e - S_d) = 0 \qquad (14)$$

where Z_b = bed elevation; and summation is over the sediment size classes. Eq. (14) can be recognized as the Exner equation with the addition of the two suspended sediment source terms. When the overall bed slope is small, the mass conservation equation for a particular size fraction for the active layer can be written as

$$\rho_s(1 - P)\frac{\partial(\beta E_m)}{\partial t} + \frac{\partial q_{b_x}}{\partial x} + \frac{\partial q_{b_y}}{\partial y} + S_e - S_d - S_F = 0 \qquad (15)$$

where q_{b_x} and q_{b_y} = x and y components of the bed load flux, respectively. The global mass conservation equation for all bed sediments then becomes

$$\rho_s(1 - P)\frac{\partial Z_b}{\partial t} + \sum\left(\frac{\partial q_{b_x}}{\partial x} + \frac{\partial q_{b_y}}{\partial y} + S_e - S_d\right) = 0 \qquad (16)$$

CH3D-SED employs the assumption that sediment particles are advected primarily by the local water velocity, except for the downward gravitational settling, which is expressed through the fall velocity. The mass conservation equation for a specific size class of suspended sediment in an elemental volume has the following form in Cartesian coordinates:

$$\frac{\partial(\rho C)}{\partial t} + \frac{\partial}{\partial x}(\rho C u) + \frac{\partial}{\partial y}(\rho C v) + \frac{\partial}{\partial z}(\rho C w) - \frac{\partial}{\partial z}(\rho C w_f)$$
$$= \frac{\partial}{\partial x}\left[D_H \frac{\partial(\rho C)}{\partial x}\right] + \frac{\partial}{\partial y}\left[D_H \frac{\partial(\rho C)}{\partial y}\right] + \frac{\partial}{\partial z}\left[D_V \frac{\partial(\rho C)}{\partial z}\right] \qquad (17)$$

where ρ = density of a mixture of water and suspended sediment (all size classes); C = dimensionless concentration, defined as the ratio of the mass, $\rho C dV$, of a particular size class of particles contained in the elemental volume, dV, to the total mass of the elemental volume; w_f = fall velocity for suspended sediment particles of a particular size class; (u, v, w) = water velocity components; D_H = horizontal mass-diffusivity coefficient; and D_V = vertical mass-diffusivity coefficient. The mass conservation equation is discretized using the quadratic upstream interpolation for convective kinematics with estimate streaming terms (Leonard 1979) method for all terms excep fall velocity and vertical mass-diffusivity. The fall velocity term is discretized using an upwind finite-difference scheme The vertical diffusion term is discretized using time weighte central differencing.

The suspended sediment erosion source, S_e, represents en trainment of active layer and bed load sediment particles int suspension. It is generally accepted that the entrainment o near-bed sediment particles into suspension can be modeled a an upward, near-bed, mass diffusion flux modified by β t reflect the availability of the particular size class in the activ layer control volume; i.e.

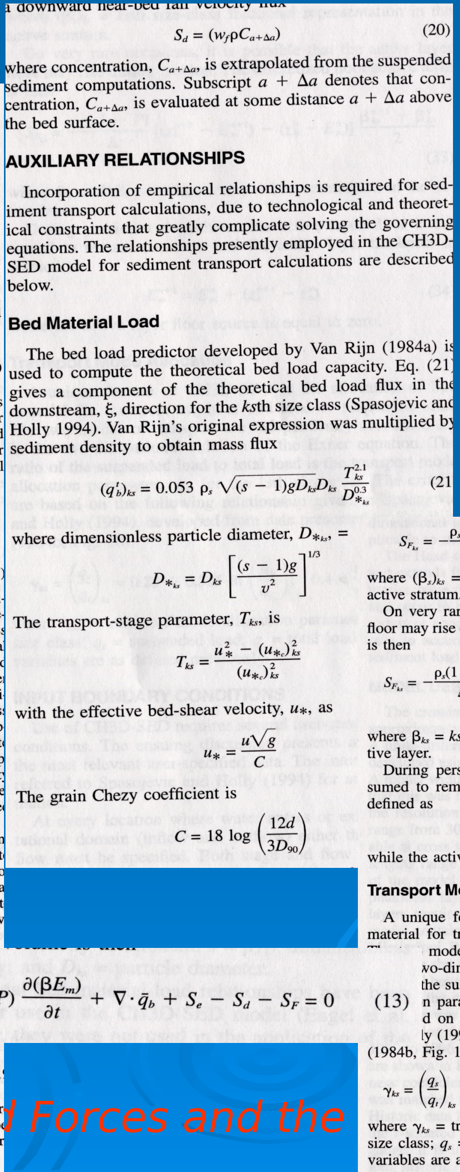
$$S_e = -\beta \left[D_V \frac{\partial(\rho}{\partial z} \right.$$

Subscript a denotes that the mass-di at a near-bed point, a, at a distance a

The suspended sediment erosion so

$$S_e = -\beta D_{V_a} \frac{(\rho C)_{a+\Delta a} - (\rho C)_a}{\Delta a} \qquad (1$$

where C_a = near-bed concentration estimated in a way to r flect the action of near-bed flow on the active layer and be load particles at a certain bed surface location. The concentr



a downward near-bed fall velocity flux

$$S_d = (w_f \rho C_{a+\Delta a}) \qquad (20)$$

where concentration, $C_{a+\Delta a}$, is extrapolated from the suspended sediment computations. Subscript $a + \Delta a$ denotes that concentration, $C_{a+\Delta a}$, is evaluated at some distance $a + \Delta a$ above the bed surface.

AUXILIARY RELATIONSHIPS

Incorporation of empirical relationships is required for sediment transport calculations, due to technological and theoretical constraints that greatly complicate solving the governing equations. The relationships presently employed in the CH3D-SED model for sediment transport calculations are described below.

Bed Material Load

The bed load predictor developed by Van Rijn (1984a) is used to compute the theoretical bed load capacity. Eq. (21) gives a component of the theoretical bed load flux in the downstream, ξ, direction for the *ks*th size class (Spasojevic and Holly 1994). Van Rijn's original expression was multiplied by sediment density to obtain mass flux

$$(q_b^t)_{ks} = 0.053\ \rho_s \sqrt{(s - 1)gD_{ks}}D_{ks} \frac{T_{ks}^{2.1}}{D_{*_{ks}}^{0.3}} \qquad (21$$

where dimensionless particle diameter, $D_{*_{ks}}$, =

$$D_{*_{ks}} = D_{ks}\left[\frac{(s - 1)g}{v^2}\right]^{1/3}$$

The transport-stage parameter, T_{ks}, is

$$T_{ks} = \frac{u_*^2 - (u_{*_c})_{ks}^2}{(u_{*_c})_{ks}^2}$$

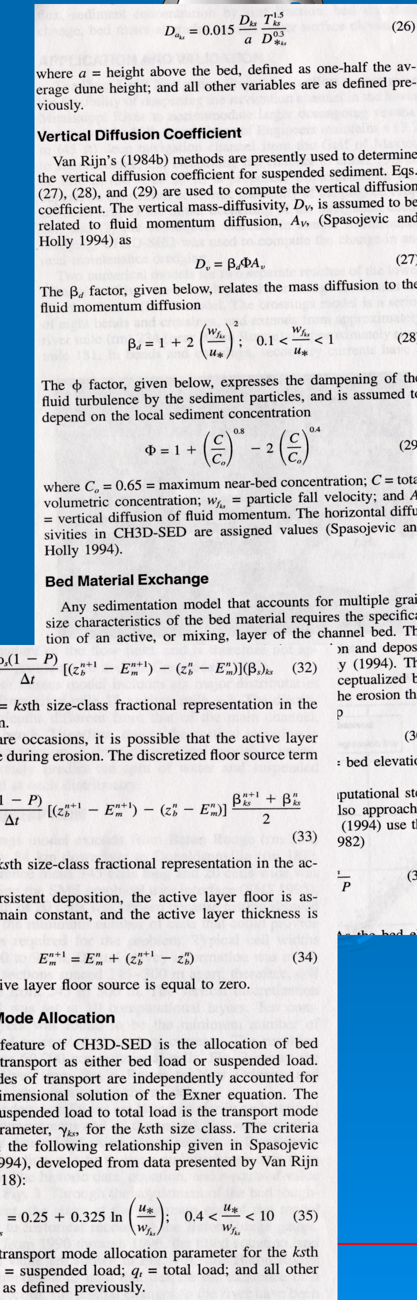
with the effective bed-shear velocity, u_*, as

$$u_* = \frac{u\sqrt{g}}{C}$$

The grain Chezy coefficient is

$$C = 18 \log\left(\frac{12d}{3D_{90}}\right)$$

$$\rho_s(1 - P)\frac{\partial(\beta E_m)}{\partial t} + \nabla \cdot \bar{q}_b + S_e - S_d - S_F = 0 \qquad (13)$$



$$D_{a_{ks}} = 0.015 \frac{D_{ks}}{a}\frac{T_{ks}^{1.5}}{D_{*_{ks}}^{0.3}} \qquad (26)$$

where a = height above the bed, defined as one-half the average dune height; and all other variables are as defined previously.

Vertical Diffusion Coefficient

Van Rijn's (1984b) methods are presently used to determine the vertical diffusion coefficient for suspended sediment. Eqs. (27), (28), and (29) are used to compute the vertical diffusion coefficient. The vertical mass-diffusivity, D_V, is assumed to be related to fluid momentum diffusion, A_V, (Spasojevic and Holly 1994) as

$$D_v = \beta_d \Phi A_v \qquad (27$$

The β_d factor, given below, relates the mass diffusion to the fluid momentum diffusion

$$\beta_d = 1 + 2\left(\frac{w_{f_{ks}}}{u_*}\right)^2; \quad 0.1 < \frac{w_{f_{ks}}}{u_*} < 1 \qquad (28$$

The ϕ factor, given below, expresses the dampening of the fluid turbulence by the sediment particles, and is assumed to depend on the local sediment concentration

$$\Phi = 1 + \left(\frac{C}{C_o}\right)^{0.8} - 2\left(\frac{C}{C_o}\right)^{0.4} \qquad (29$$

where $C_o = 0.65$ = maximum near-bed concentration; C = tota volumetric concentration; $w_{f_{ks}}$ = particle fall velocity; and A = vertical diffusion of fluid momentum. The horizontal diffu sivities in CH3D-SED are assigned values (Spasojevic an Holly 1994).

Bed Material Exchange

Any sedimentation model that accounts for multiple grai size characteristics of the bed material requires the specifica tion of an active, or mixing, layer of the channel bed. Th

$$S_{F_{ks}} = -\frac{\rho_s(1 - P)}{\Delta t}[(z_b^{n+1} - E_m^{n+1}) - (z_b^n - E_m^n)](\beta_s)_{ks} \qquad (32)$$

where $(\beta_s)_{ks}$ = *ks*th size-class fractional representation in the active stratum.

On very rare occasions, it is possible that the active layer floor may rise during erosion. The discretized floor source term is then

$$S_{F_{ks}} = -\frac{\rho_s(1 - P)}{\Delta t}[(z_b^{n+1} - E_m^{n+1}) - (z_b^n - E_m^n)]\frac{\beta_{ks}^{n+1} + \beta_{ks}^n}{2} \qquad (33)$$

where β_{ks} = *ks*th size-class fractional representation in the active layer.

During persistent deposition, the active layer floor is assumed to remain constant, and the active layer thickness is defined as

$$E_m^{n+1} = E_m^n + (z_b^{n+1} - z_b^n) \qquad (34)$$

while the active layer floor source is equal to zero.

Transport Mode Allocation

A unique feature of CH3D-SED is the allocation of bed material for transport as either bed load or suspended load. T modes of transport are independently accounted for wo-dimensional solution of the Exner equation. The the suspended load to total load is the transport mode n parameter, γ_{ks}, for the *ks*th size class. The criteria d on the following relationship given in Spasojevic ly (1994), developed from data presented by Van Rijn (1984b, Fig. 18):

$$\gamma_{ks} = \left(\frac{q_s}{q_t}\right)_{ks} = 0.25 + 0.325 \ln\left(\frac{u_*}{w_{f_{ks}}}\right); \quad 0.4 < \frac{u_*}{w_{f_{ks}}} < 10 \qquad (35)$$

where γ_{ks} = transport mode allocation parameter for the *ks*th size class; q_s = suspended load; q_t = total load; and all other variables are as defined previously.

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d Forces and the

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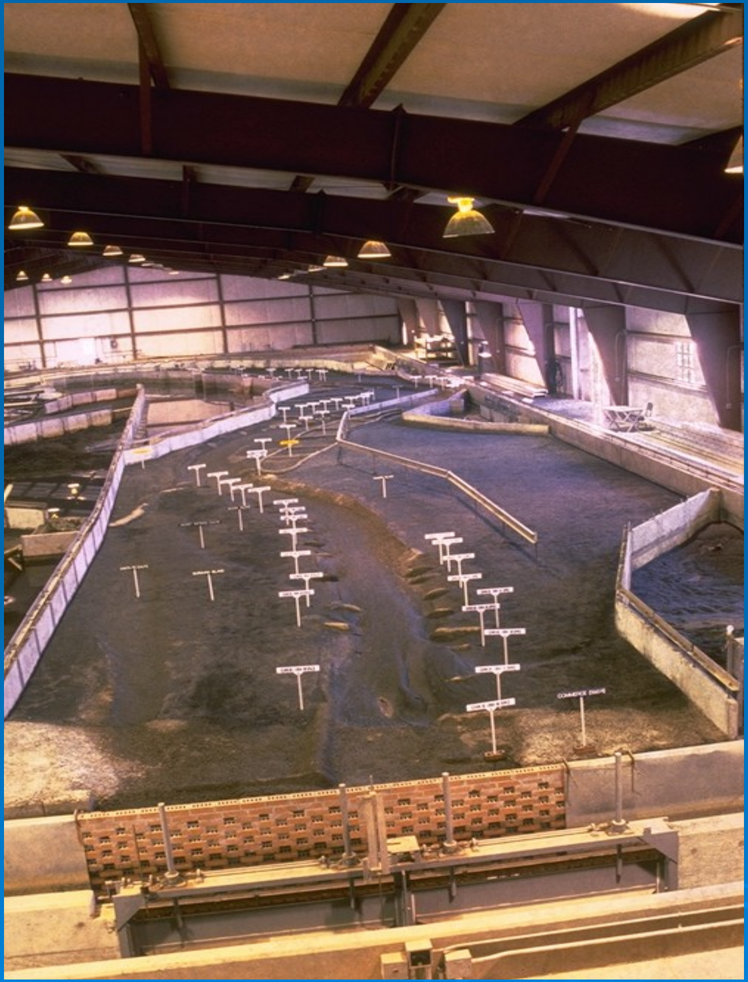
of Engineers®

Traditional Physical River Modeling



Traditional Movable Bed Models

- Excellent Tool to Examine Trends in the Riverbed
- Very Large
- Very Expensive
- Lengthy Studies

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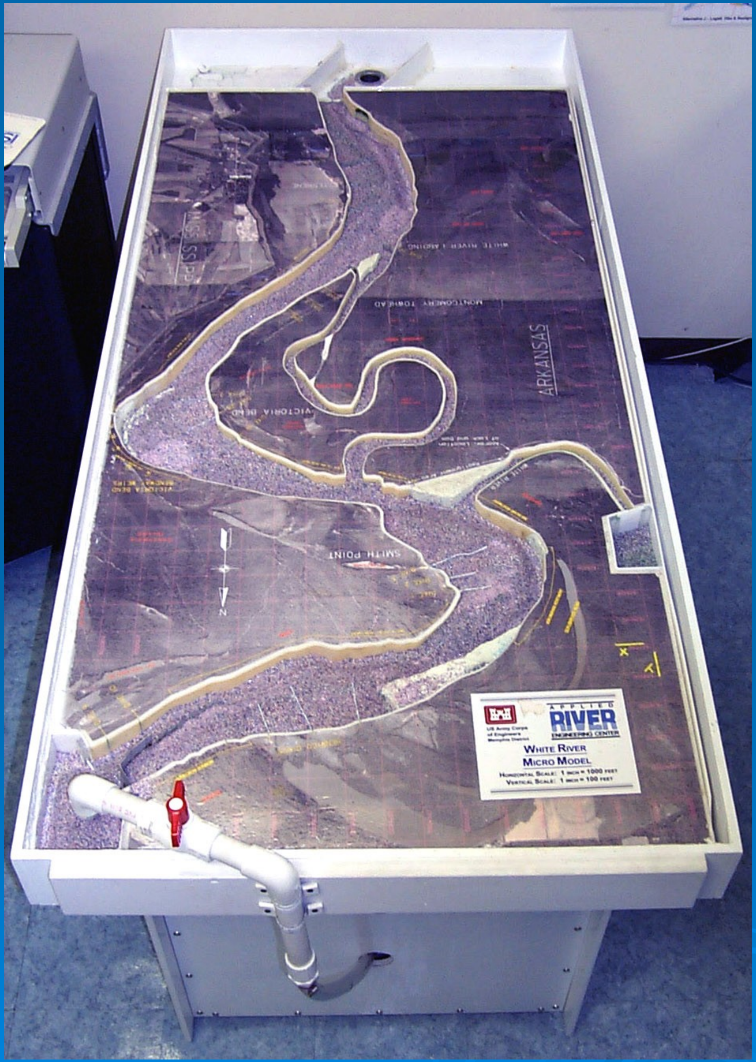
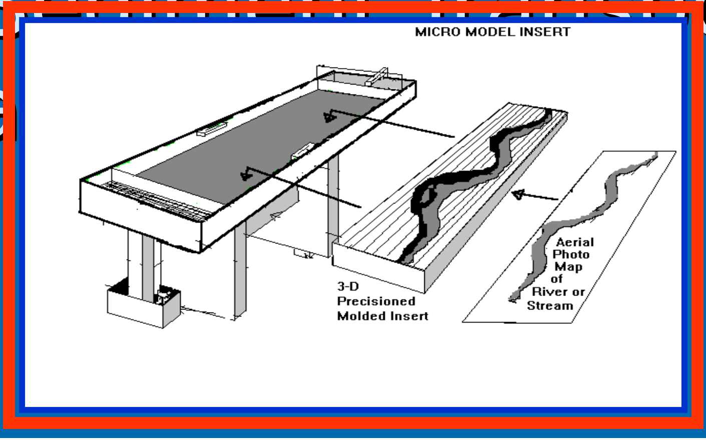
HSR Modeling


ARKANSAS
SMITH POINT
VICTORIA BEND
MONTGOMERY TOWHEAD
WHITE RIVER LANDING
US Army Corps of Engineers Memphis District
APPLIED RIVER ENGINEERING CENTER
White River
Micro Model
Horizontal Scale: 1 inch = 1000 feet
Vertical Scale: 1 inch = 100 feet

Micro Modeling is Small Scale Physical Sediment Transport Modeling of a River or Stream

- Table Top Size
- Three Dimensional Bed Response
- Flow Visualization of Surface Velocity Trends
- Every Part of the Model is Visible, Dynamic, and in Real Time
- Relatively Inexpensive
- Results Usually Obtained within a few months

Method And Apparatus For HSR Modeling The Sediment Transport
Cha
River


MICRO MODEL INSERT
3-D Precisioned Molded Insert
Aerial Photo Map of River or Stream

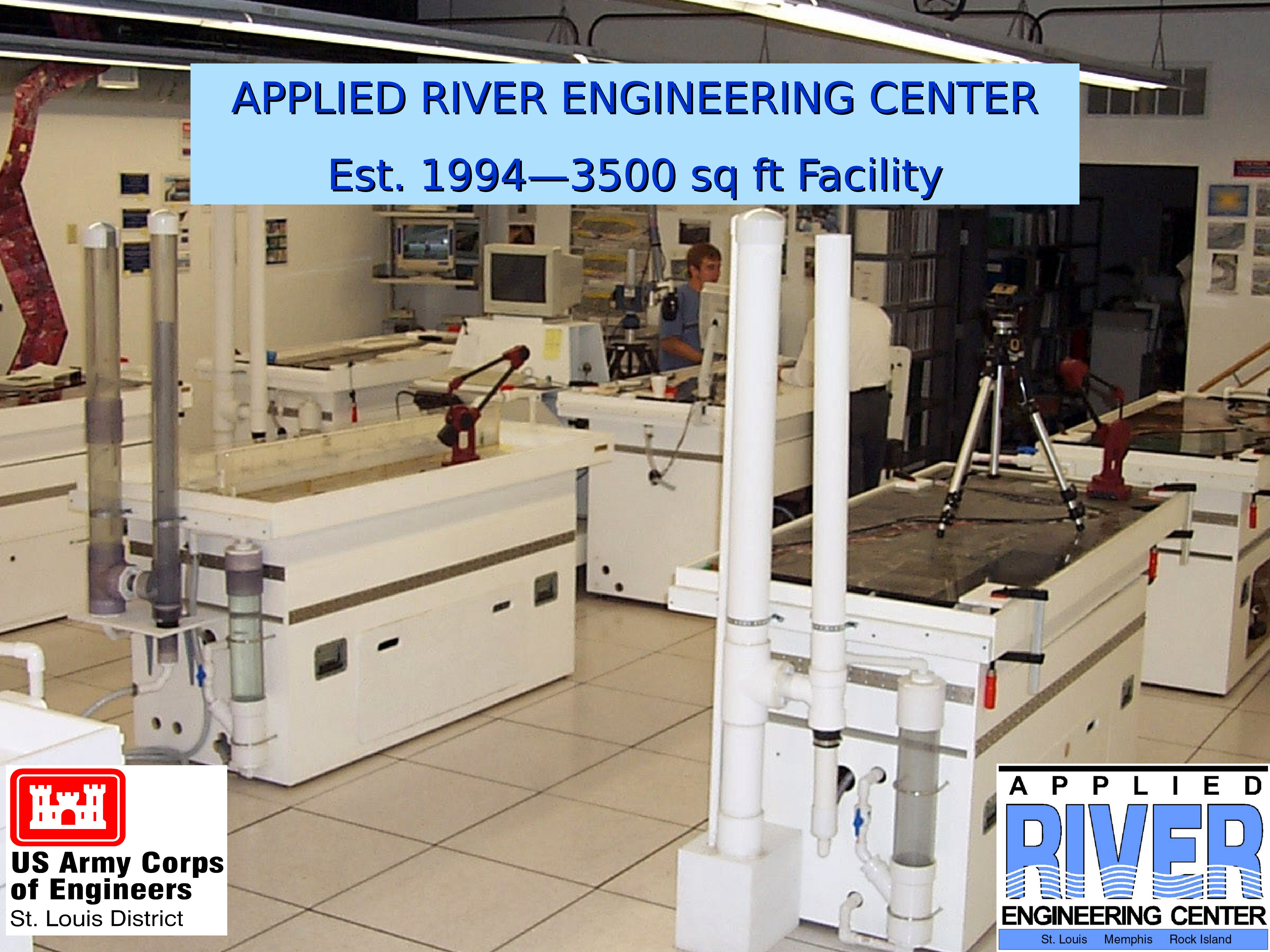
United States Patent

5,653,592

Aug 5, 1997

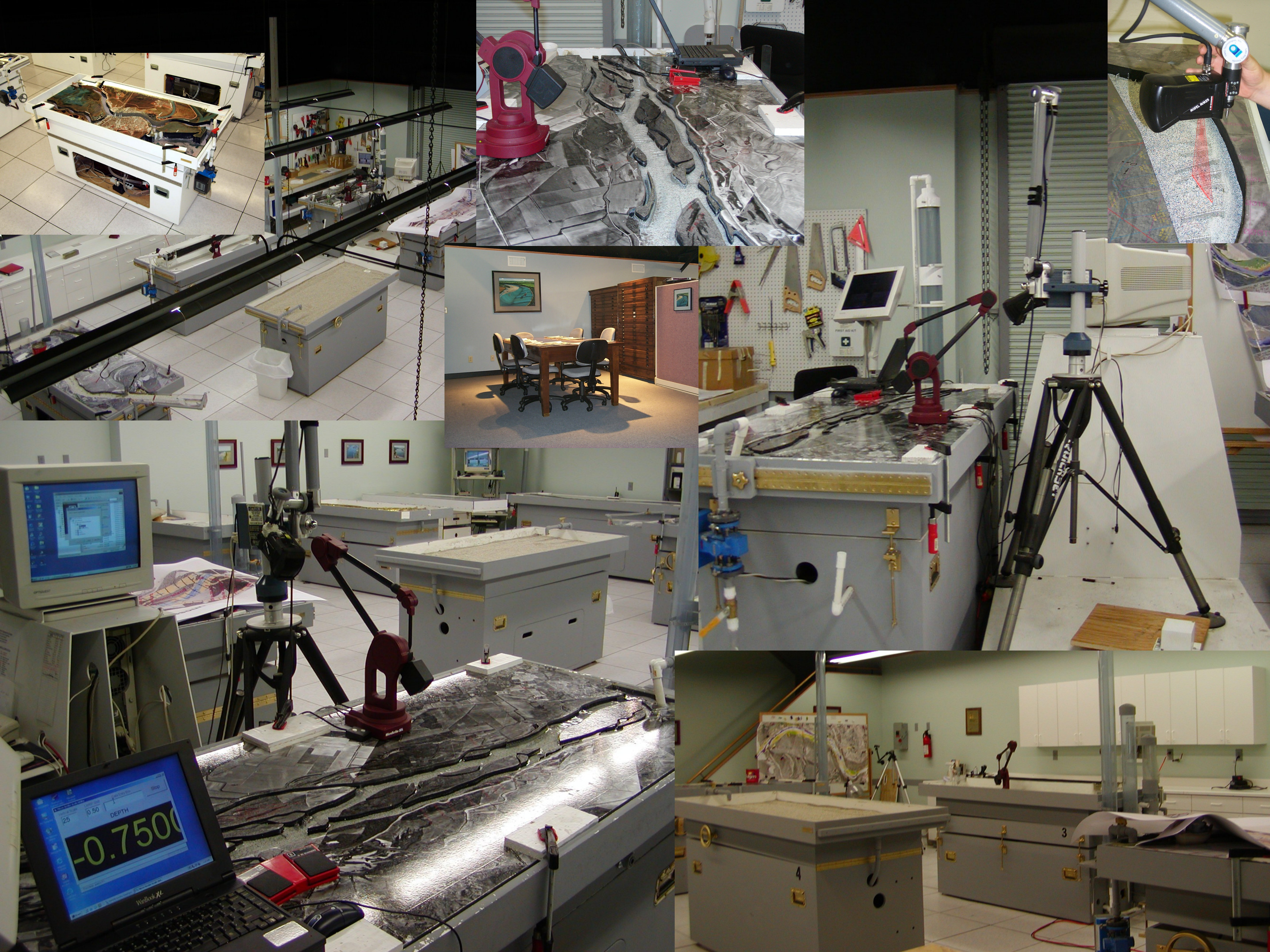
APPLIED RIVER ENGINEERING CENTER

Est. 1994—3500 sq ft Facility



US Army Corps of Engineers
St. Louis District

APPLIED RIVER ENGINEERING CENTER
St. Louis Memphis Rock Island


MODEL MAKER
FIRST AID KIT
25
0.50
DEPTH
-0.7500
WinBook XL
3
4

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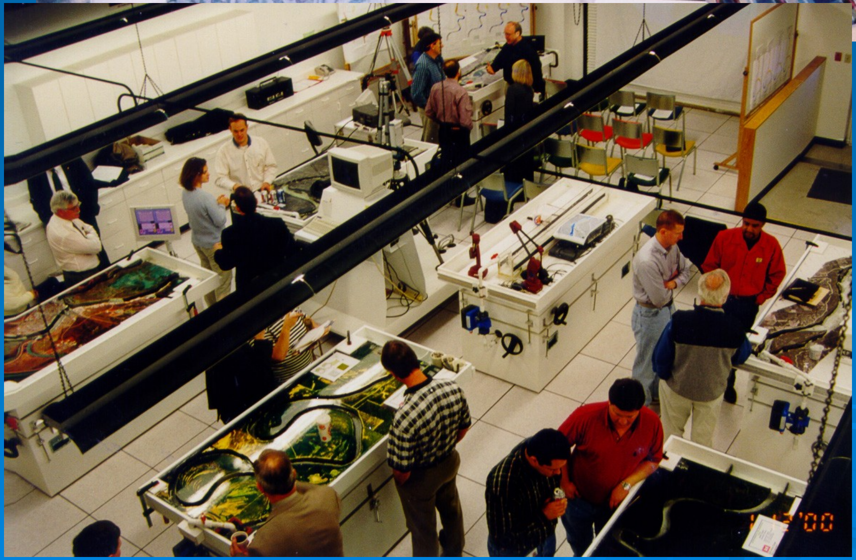
Customer Outreach & Plan Formulation with HSR Models



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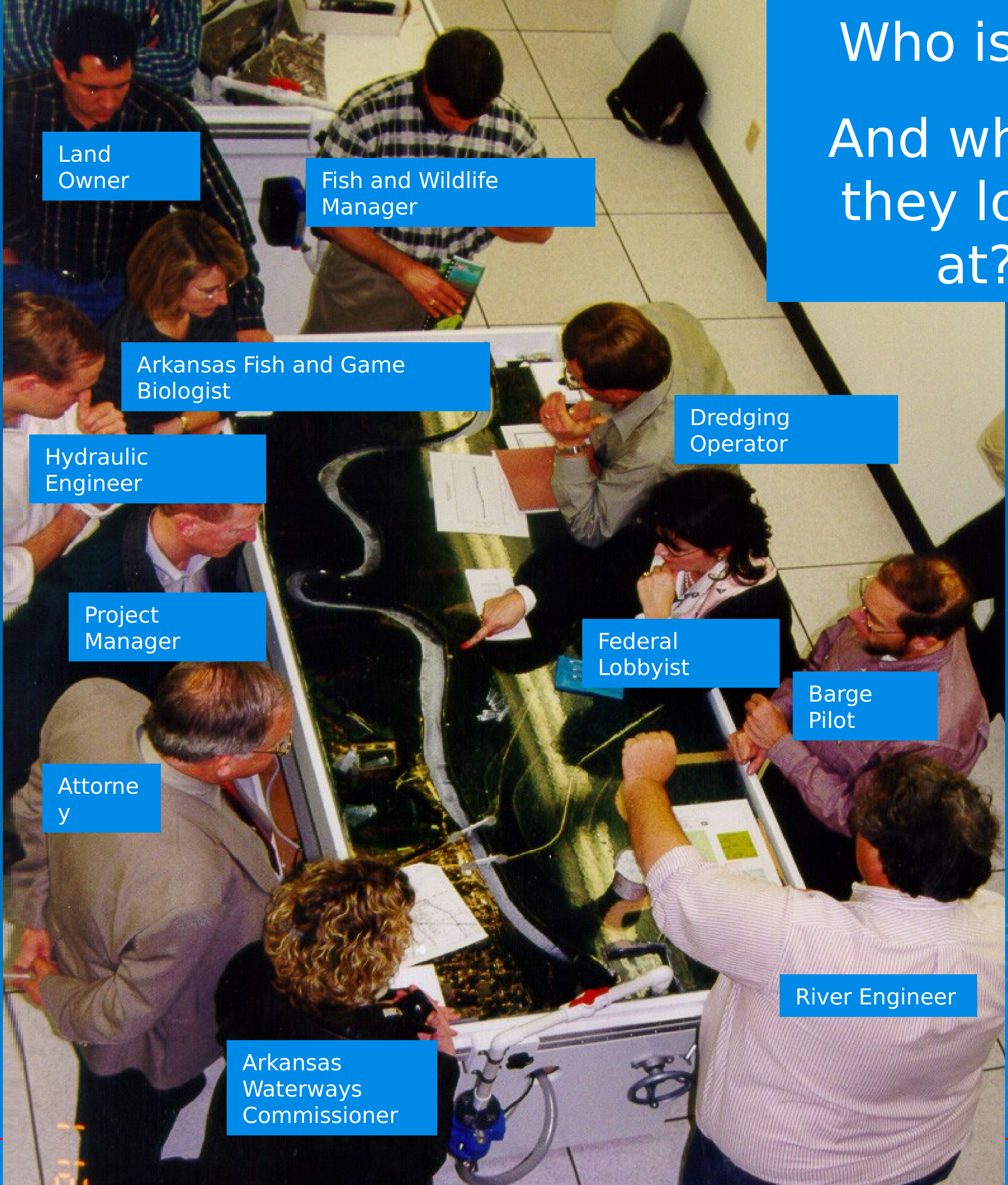
Who is who?

And what are they looking at???


Land Owner
Fish and Wildlife Manager
Arkansas Fish and Game Biologist
Dredging Operator
Hydraulic Engineer
Project Manager
Federal Lobbyist
Barge Pilot
Attorne y
River Engineer
Arkansas Waterways Commissioner

US Army Corps
of Engineers®

Partnering Agencies

**US Army Corps
of Engineers**
St. Louis District

Missouri Conservation Department

Illinois Department of Natural Resources

U.S. Fish & Wildlife Service

***R**iver*
***I**ndustry*
***A**ction*
***C**ommittee*

United States Environmental Protection Agency

American Land Conservancy

Additional Environmental measures have been formulated among above St. Louis District partners since 1994.

All measures have been engineered to gain maximum environmental benefits while ensuring no negative impacts to the navigation channel.

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International Outreach

German Delegation

Japan
Delegation

Dutch
Delegation

One Corps Serving the Armed Forces and the Nation

US Army Corps of Engineers®

Community Outreach

One Corps Serving the Armed Forces and the Nation

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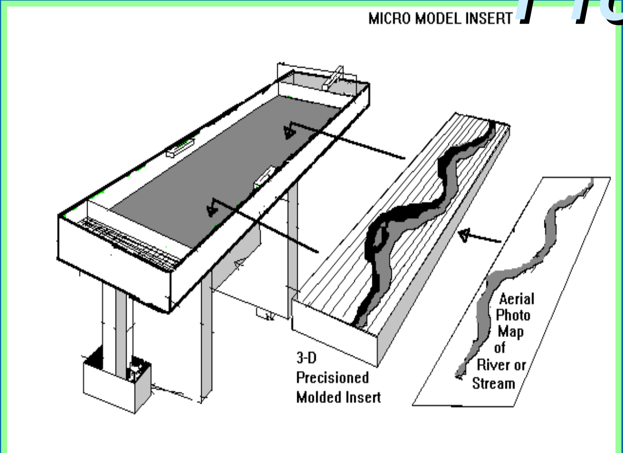
HSR Modeling Theory

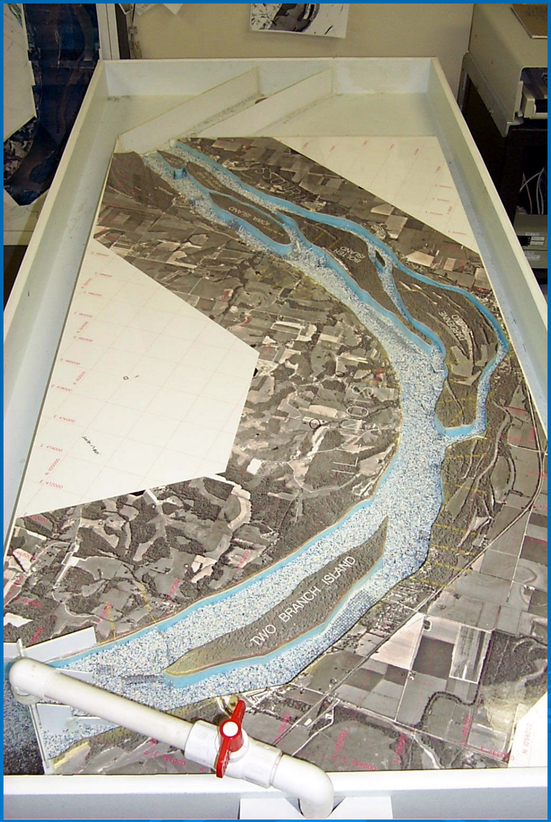
THE BASIC SCIENTIFIC PRINCIPLE

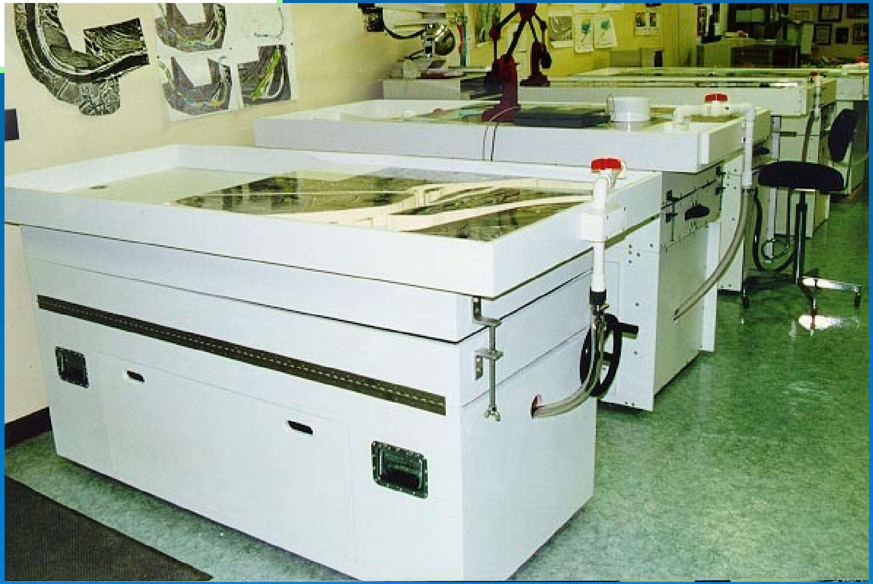
A River, No Matter How Large or Small, is a Body of Flowing Water and Sediment.

The Mechanics of Moving Water & Sediment Remain Similar, Whether it's the Mississippi or a Small Stream

Hydraulic Tabletop Flume and Inserts


MICRO MODEL INSERT
3-D Precisioned Molded Insert
Aerial Photo Map of River or Stream


TWO BRANCH ISLAND



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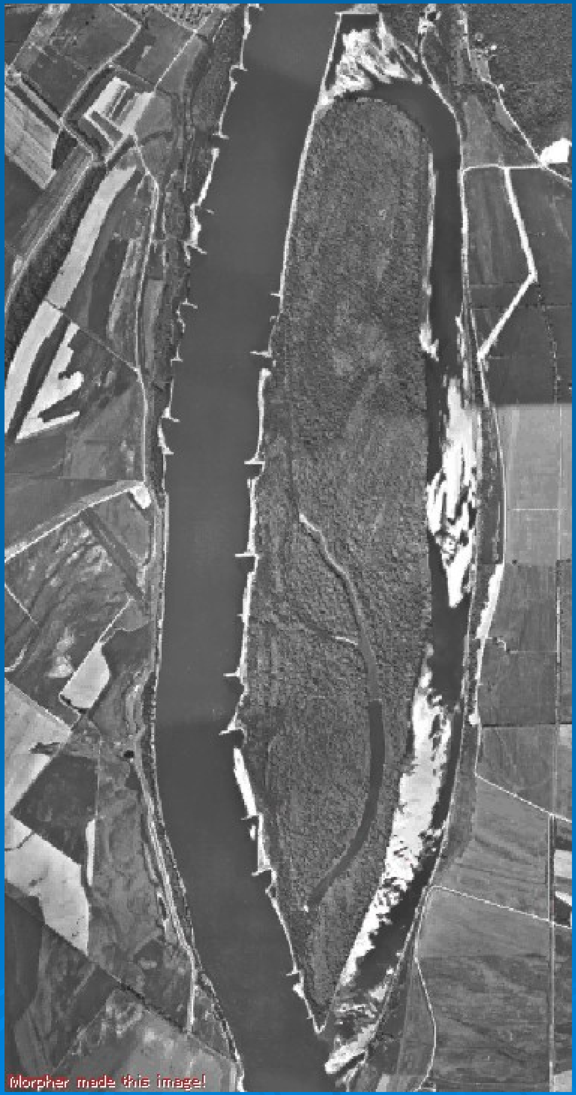
The Planform Insert


Morpher made this image!

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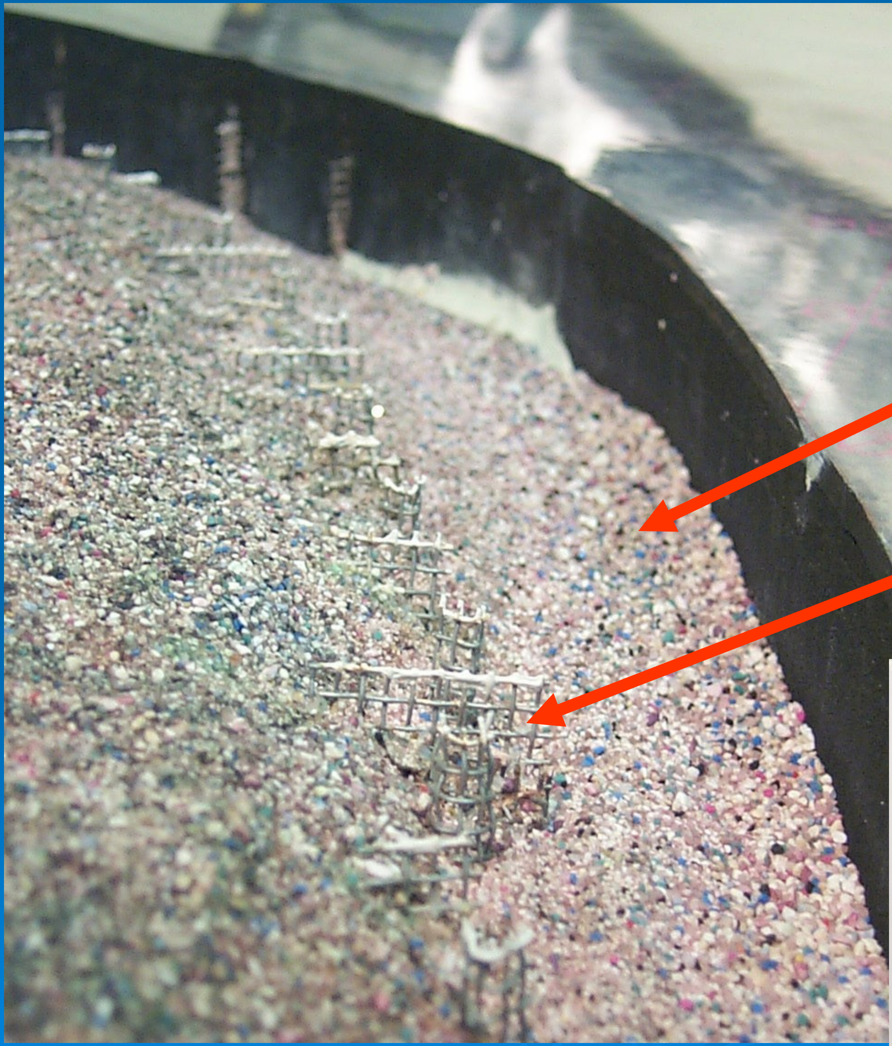
The Riverbed

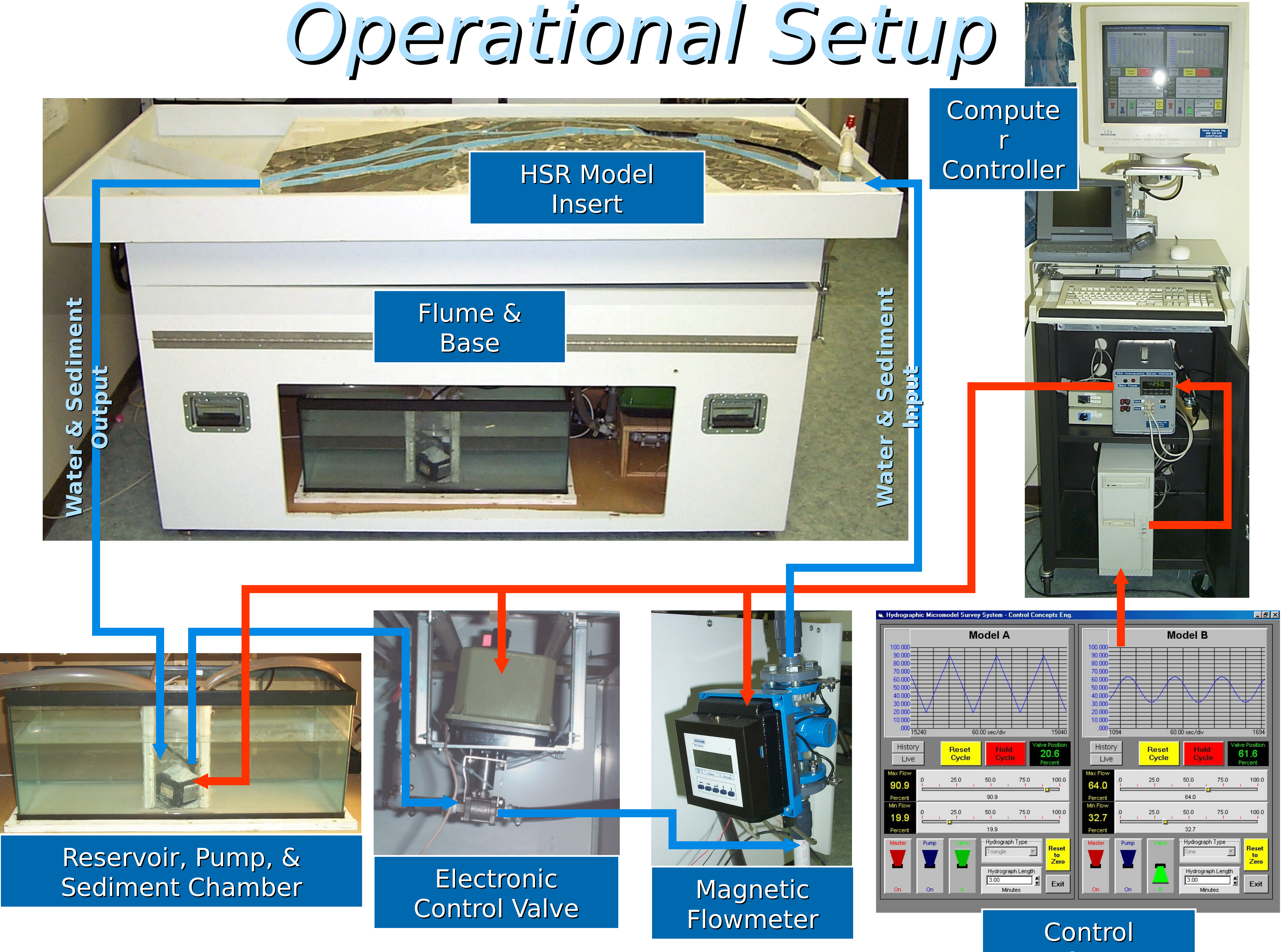


Granular Plastic Sediment Simulates River Sediment

Steel Mesh Structures Simulate River

PLASTI-GRIT®
UREA-TYPE II
COMPOSITION MATERIALS CO., INC.
MESH
PG-1 12/16
PG-2 16/20
PG-3 20/30
PG-4 30/40
PG-5 40/60

Operational Setup



HSR Model Insert

Flume & Base

Computer Controller

Water & Sediment Output

Water & Sediment Input

Reservoir, Pump, & Sediment Chamber

Electronic Control Valve

Magnetic Flowmeter

Control

Hydrographic Micromodel Survey System - Control Concepts Eng.

Model A

Valve Position: 20.6 Percent

Max Flow: 90.9 Percent

Min Flow: 19.9 Percent

Master: On

Pump: On

Valve: A

Hydrograph Type: Triangle

Hydrograph Length: 3.00 Minutes

Model B

Valve Position: 61.6 Percent

Max Flow: 64.0 Percent

Min Flow: 32.7 Percent

Master: On

Pump: On

Valve: B

Hydrograph Type: Sine

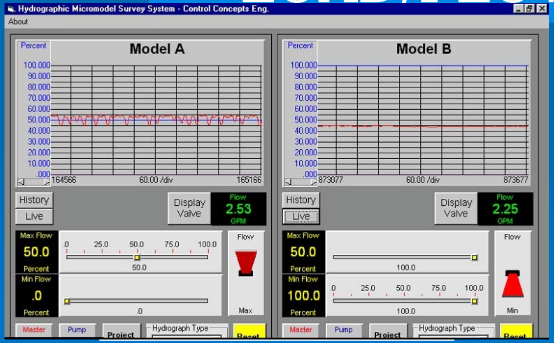
Hydrograph Length: 3.00 Minutes

100.000
90.000
80.000
70.000
60.000
50.000
40.000
30.000
20.000
10.000
.000
15240
60.00 sec/div
15840
1094
1694
History
Live
Reset Cycle
Hold Cycle
.0
25.0
50.0
75.0
100.0
Reset to Zero
Exit

Study of Average Conditions or Within Channel Flows

The Electronic Flow Control System Enables Precision Control of Water and Sediment

SEDIMENT LOAD/FLOW **IN** = SEDIMENT LOAD/FLOW **OUT**

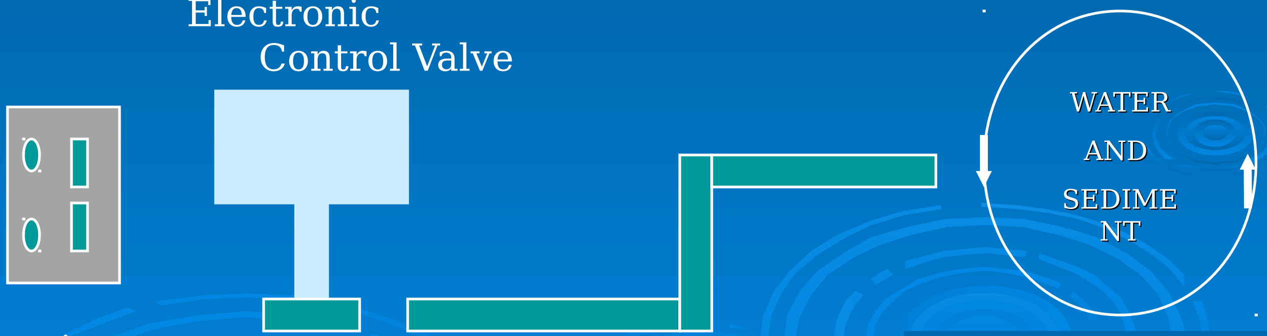

Hydrographic Micromodel Survey System - Control Concepts Eng.

Model A: Flow 2.53 GPM; Max Flow 50.0 Percent; Min Flow .0 Percent

Model B: Flow 2.25 GPM; Max Flow 50.0 Percent; Min Flow 100.0 Percent

About
Percent
Model A
Model B
100.000
90.000
80.000
70.000
60.000
50.000
40.000
30.000
20.000
10.000
.000
164566
60.00 /div
165166
873077
873677
History
Live
Display Valve
Flow
Max
Min
.0
25.0
50.0
75.0
100.0
Master
Pump
Project
Hydrograph Type
Reset

CPU

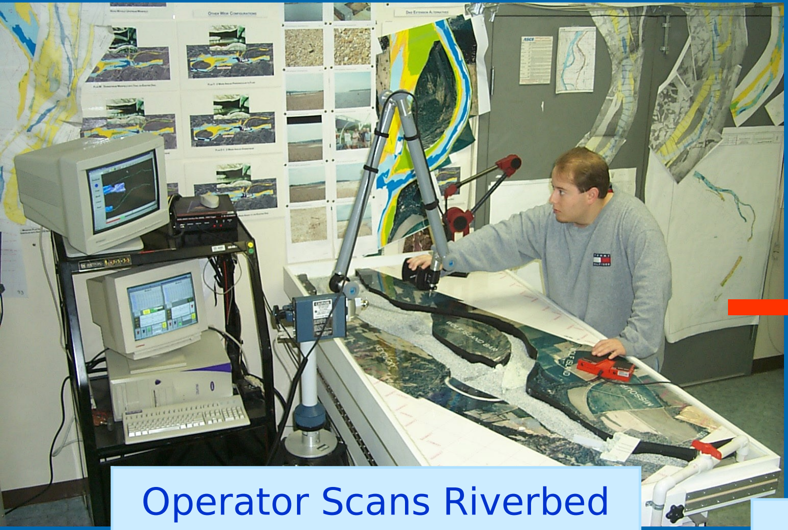

Electronic Control Valve

WATER AND SEDIMENT

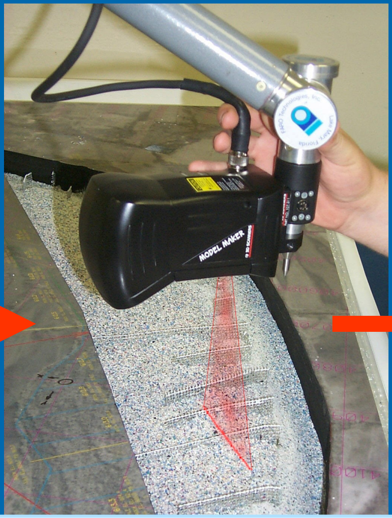
Electronic Interface

Repeatable, Balanced Model Response

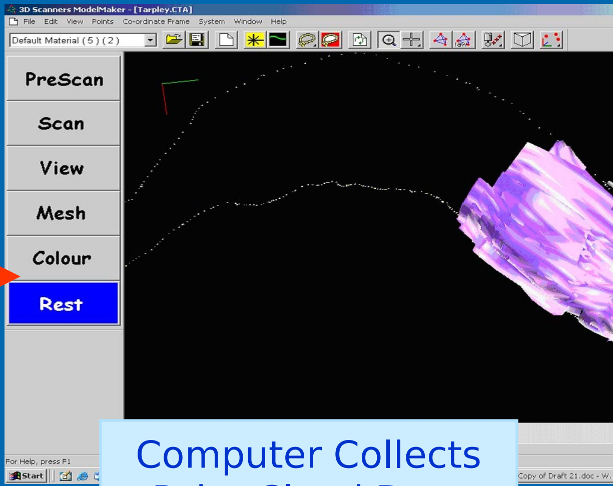
Model Data Collection with 3-D Scanners



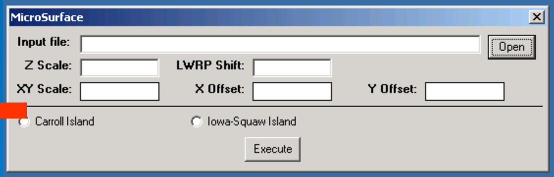
Operator Scans Riverbed



Laser Records 1 million pts.


3D Scanners ModelMaker - [Tarpley.CTA]
File Edit View Points Co-ordinate Frame System Window Help
Default Material (5) (2)
PreScan
Scan
View
Mesh
Colour
Rest
For Help, press F1
Start

Computer Collects Point Cloud Data



MicroSurface

Input file:

Z Scale:

LWRP Shift:

XY Scale:

X Offset:

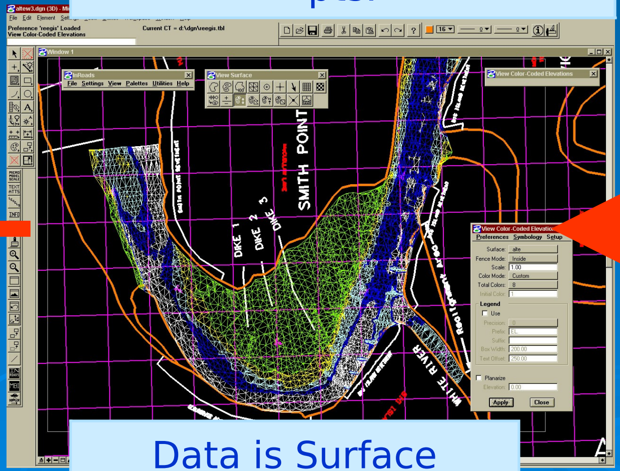
Y Offset:

○ Carroll Island

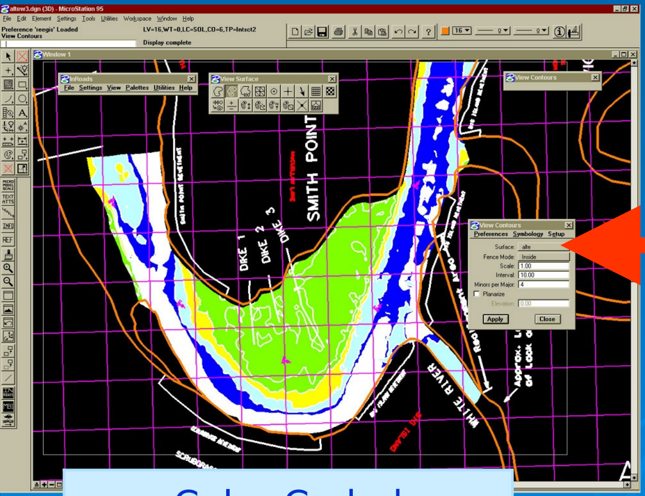
○ Iowa-Squaw Island

Open
Execute

Raw Data is Scaled to Real World Dimensions


altew3.dgn (3D) - MicroStation 95
View Color-Coded Elevations
DIKE 1
DIKE 2
DIKE 3
SMITH POINT
WHITE RIVER
Apply
Close

Data is Surface Modeled in CADD


altew3.dgn (3D) - MicroStation 95
View Contours
DIKE 1
DIKE 2
DIKE 3
SMITH POINT
WHITE RIVER
Apply
Close

Surface: alte

Fence Mode: Inside

Scale: 1.00

Interval: 10.00

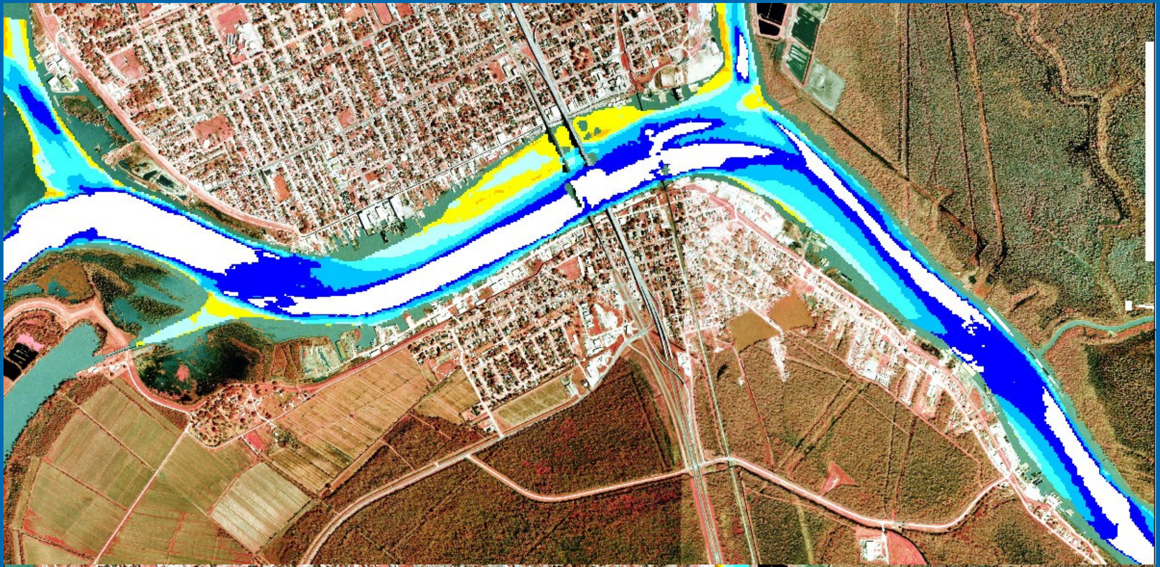
Minors per Major: 4

Color Coded Contours are Applied

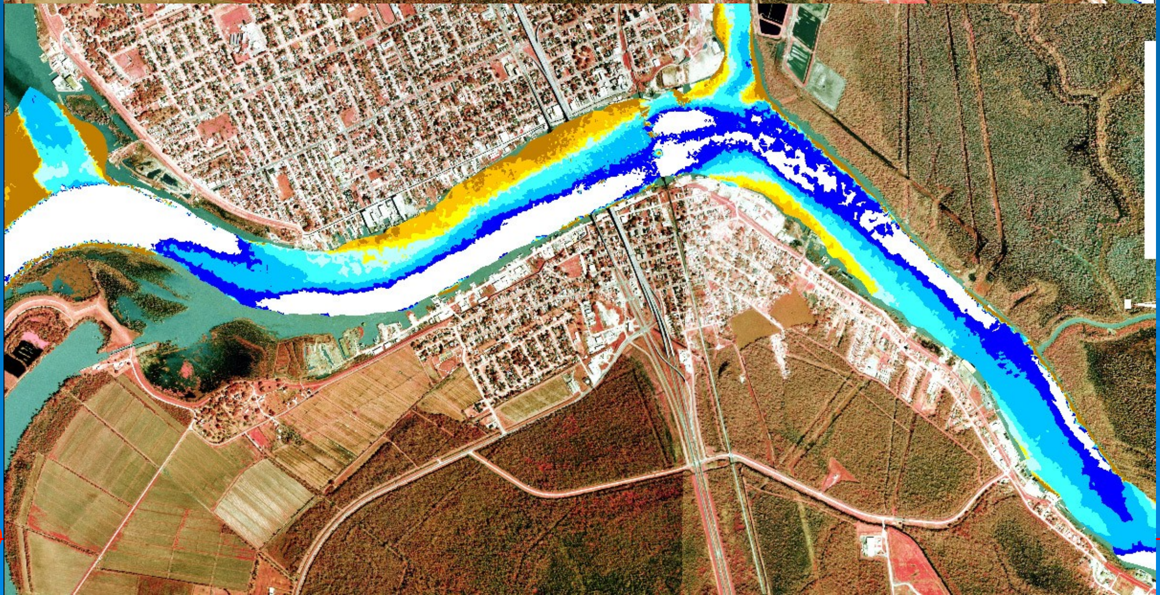
Model Data Analysis

Reproduction of the Riverbed

1999 Survey of the River Bed



Survey of the Model Riverbed



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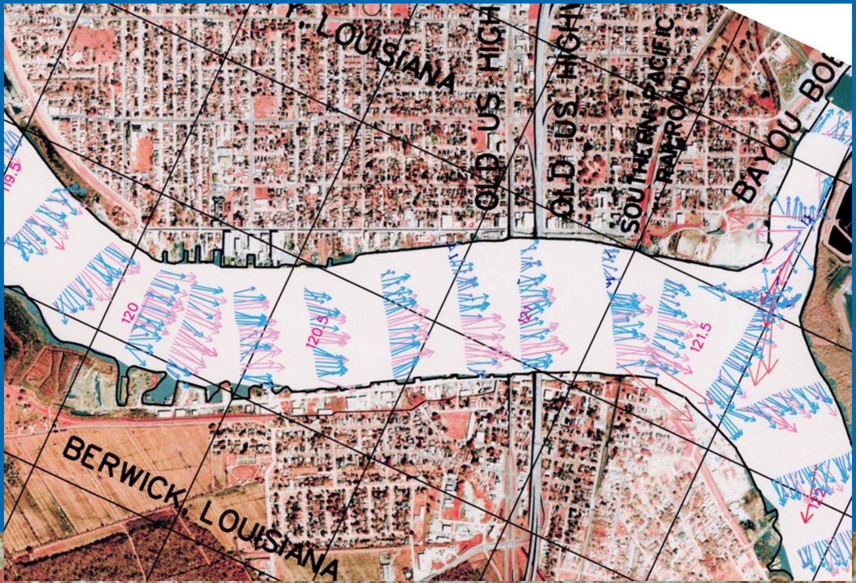
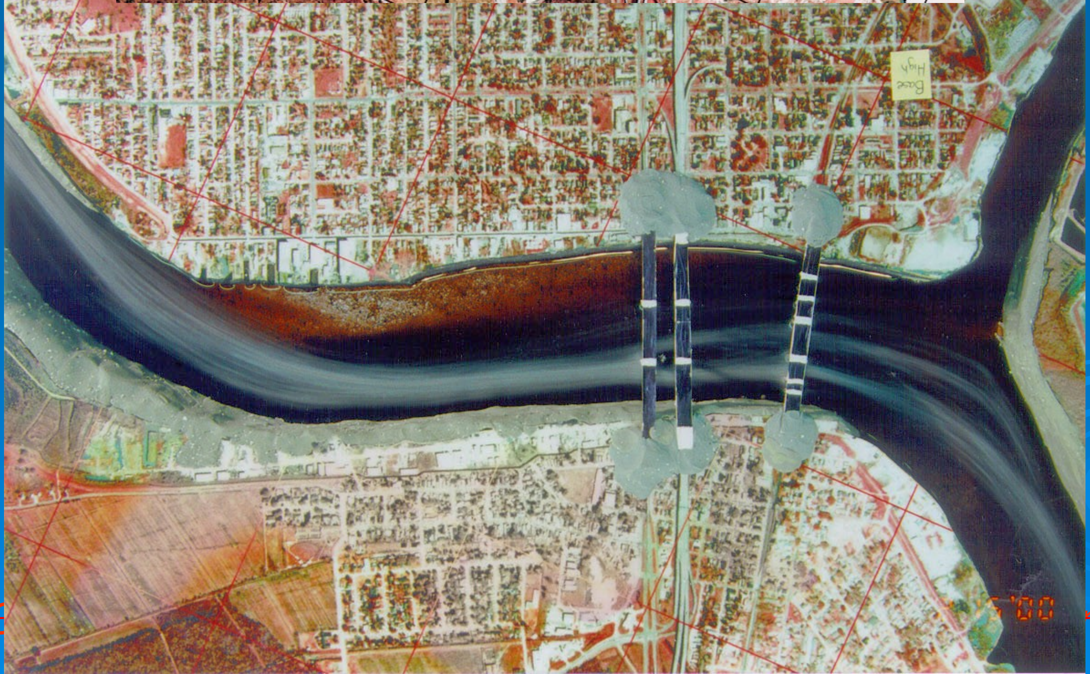
Flow Visualization

Velocity Vectors in the River


LOUISIANA
OLD US HIGH
OLD US HIGHW
SOUTHERN PACIFIC RAILROAD
BAYOU BOE
119.5
120
120.5
121
121.5
122
BERWICK, LOUISIANA

Flow Lines in the Model


Base High
5'00

Applications

- Studying the Flow and Sediment Response of Rivers and Streams to improve navigation and the environment.
- Effects of Training Structures
- Environmental Restoration of Rivers
- Dredging Impacts, i.e. Excavating and Disposal
- Meandering
- Bridge Scour
- Improvements to Harbors and Water Intakes
- Impact Assessment and Improvement To Impo
Point Sources

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Why HSR Modeling?

- Time and Cost
- Physical Processes versus Mathematical
- Visual Communication to the Public
- Education
- Experimentation and Design Alternative Impacts

What are We Modeling?

- Three Dimensional Bed Distribution Pattern or Ultimate Bed Configuration within the Channel
- Relative Velocity Distribution which forms the Bed Distribution
- Resultant Plan View Far-Field Flow Patterns

Power of the Tool

- Assess average expected sediment response with and without structural modification
- Assess average expected flow response using flow visualization